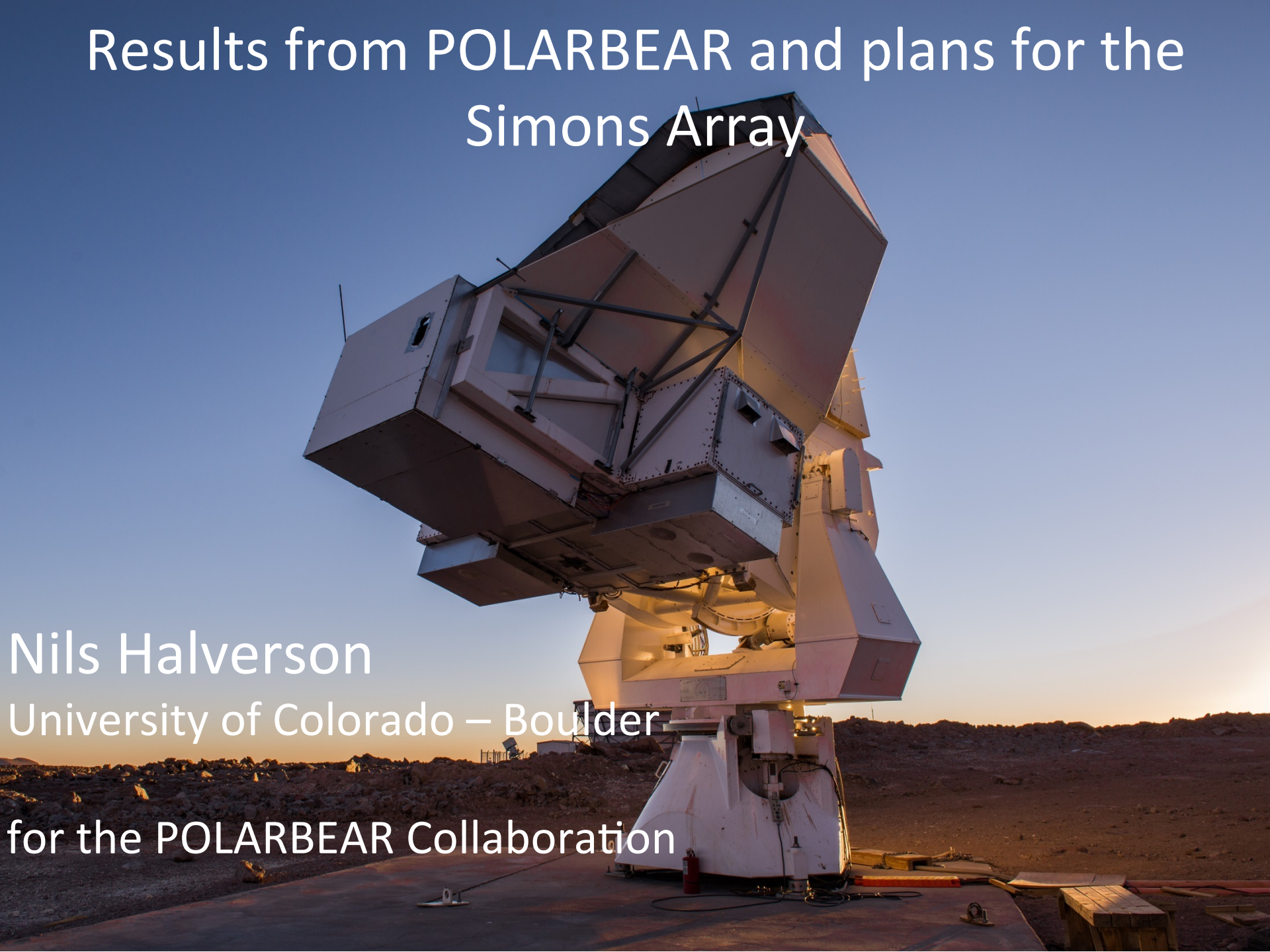
Results from POLARBEAR and plans for the Simons Array



Nils Halverson
University of Colorado – Boulder

for the POLARBEAR Collaboration

POLARBEAR Collaboration

MEXT
SIMONS FOUNDATION
Advancing Research in Basic Science and Mathematics

CONICYT
NSF
NASA

UC Berkeley
Brian Barch
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Tijmen de Haan
Josquin Errard
Neil Goeckner-Wald
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Yasuto Hori
Oliver Jeong
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Mike Myers
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Ian Shirley
Bryan Steinbach
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Akito Kusaka
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Satoru Takakura
Takayuki Tomaru

SOKENDAI
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Maude Le Jeune
Julien Peloton
Davide Poletti
Radek Stompor

Argonne NL
Amy Bender

Cardiff U.
Peter Ade

McGill University
Matt Dobbs
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Graeme Smecher

Dalhousie
Scott Chapman
Colin Ross
Kaja Rotermund
Alexei Tikhomirov

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Nobuhiko Katayama
Kuniyoshi Mizukami
Haruki Nishino

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Stephen Feeney
Andrew Jaffe

U. Melbourne
Christian Reichardt

SISSA
Carlo Baccigalupi
Giulio Fabbian
Giuseppe Puglisi

JAXA
Tomotake Matsumura

UC Irvine
Chang Feng

National Institute for Fusion Science
Suguru Takada

Cardiff University
Peter Ade

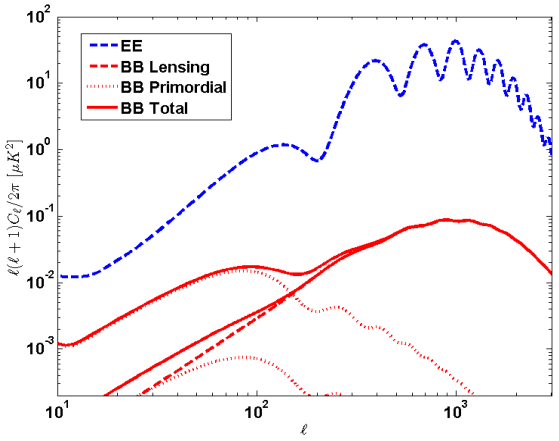
NASA Goddard
Nathan Miller

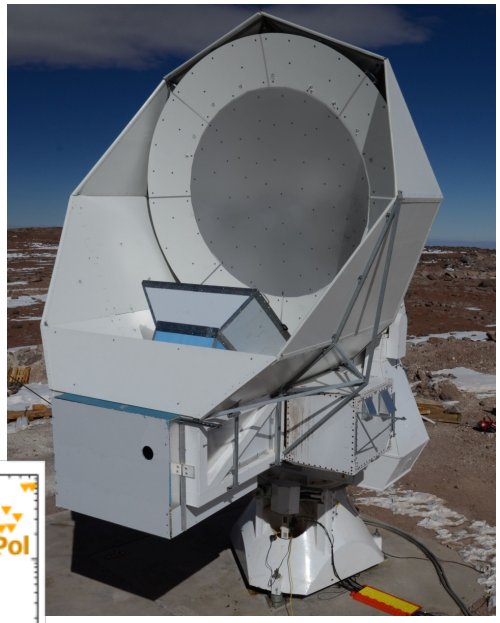
Princeton
Zigmund Kermish

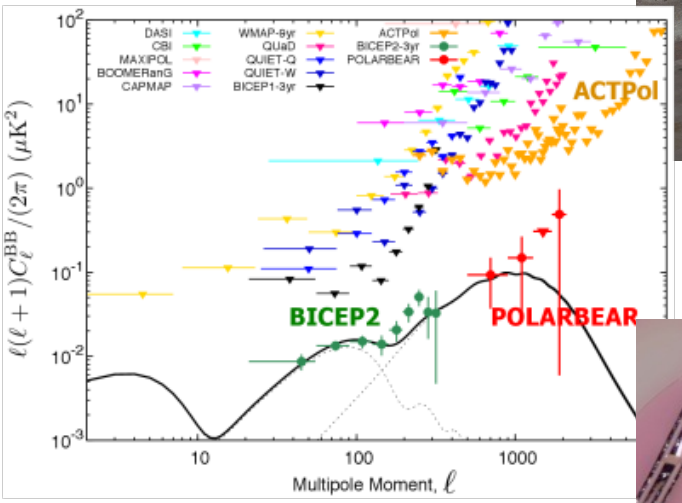
Católica (PUC)
David Boettger
Rolando Dunner

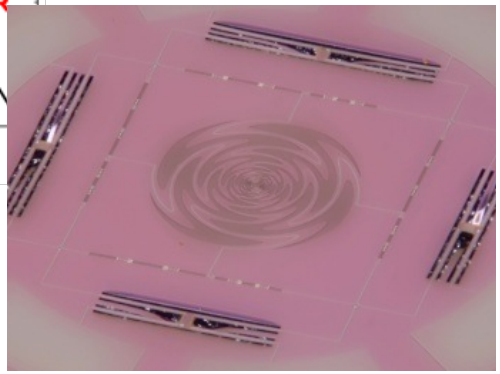
And many more in years past

Outline



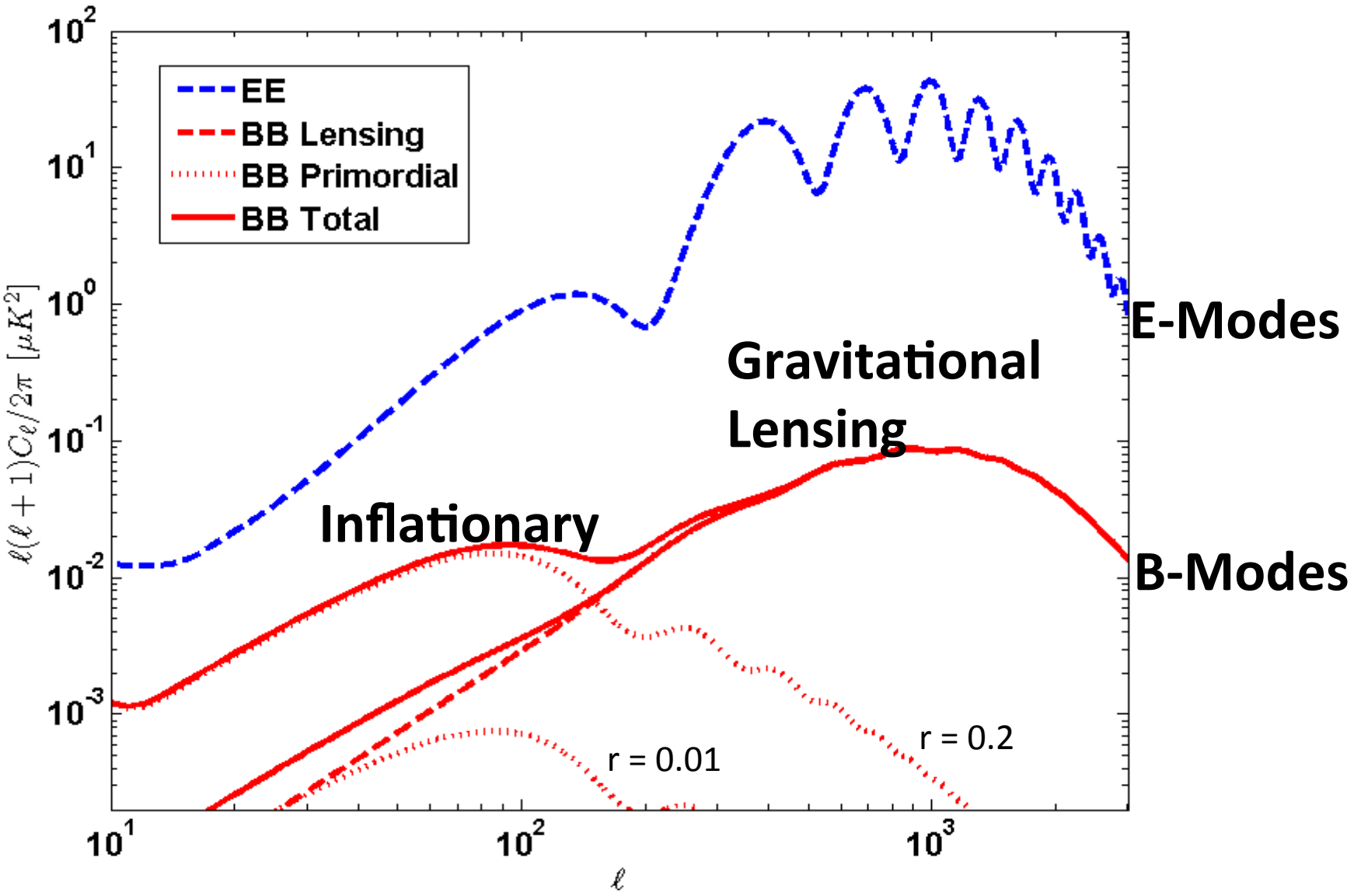






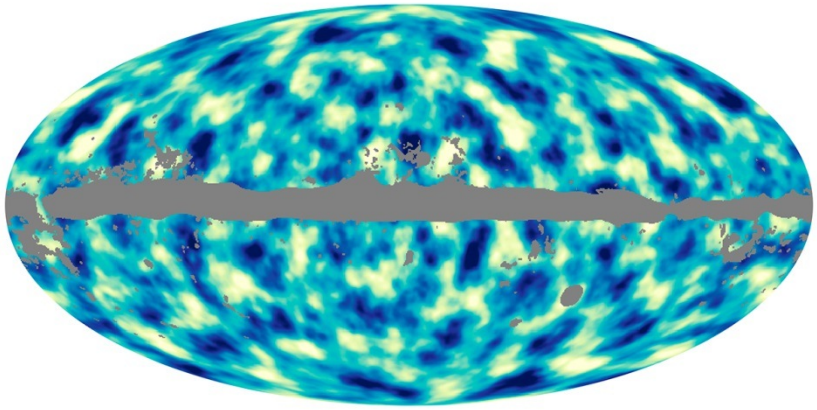
- Scientific goals
- The POLARBEAR instrument
- First season results
- The next generation instrument: PB2/ Simons Array

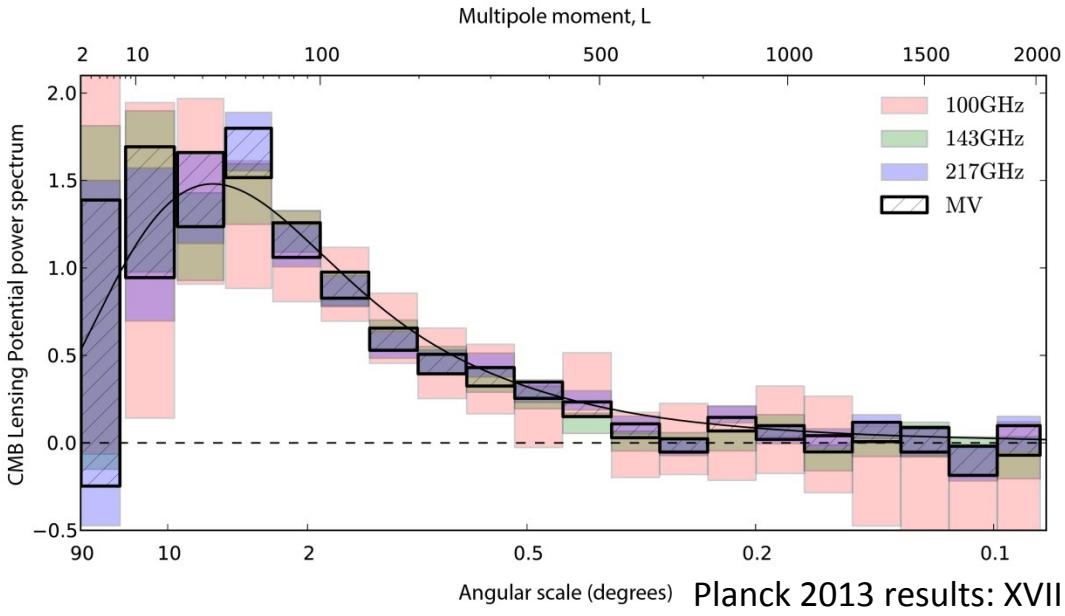
Predicted Polarization Power Spectrum



Lensing potential map from correlating across angular scales in T,E,B

- Reconstruct gravitational potential
- Lensing potential power spectrum:
  - Neutrino mass
  - Dark energy
- Deflection map:
  - De-lensing





Planck 2013 results: XVII

POLARBEAR Instrument Design: Telescope

Angular resolution to characterize lensing, 3.5’ @ 150 GHz

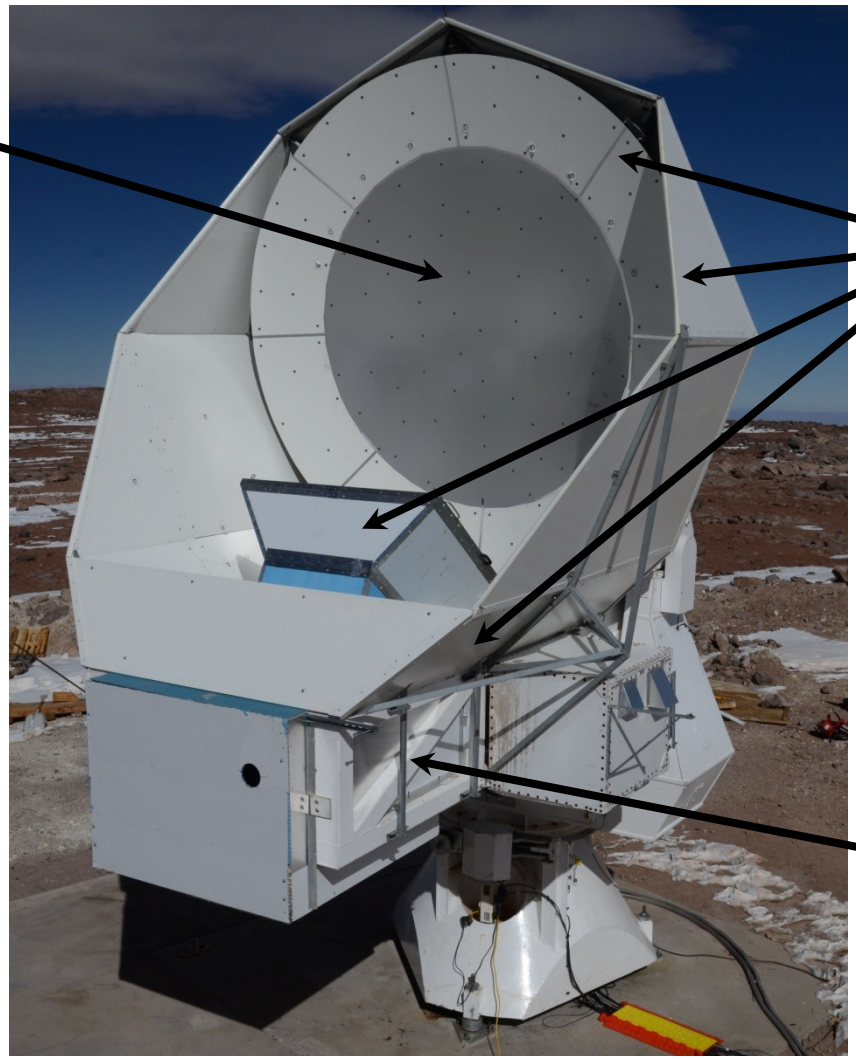
Off-axis Gregorian-Dragone:

-Low cross polarization

-Large field of view

-Large throughput

Huan Tran Telescope

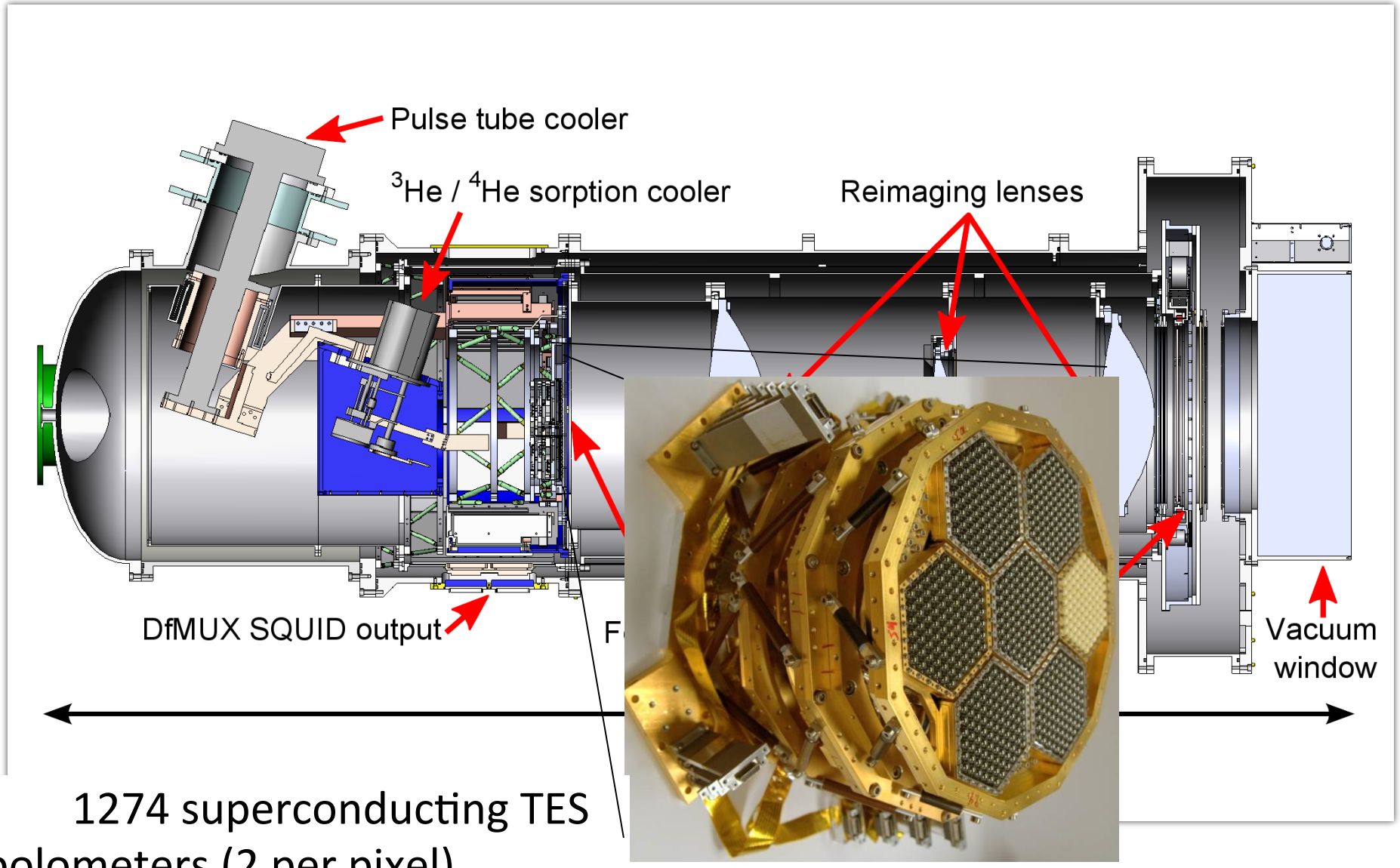


Elevation: 5200 m

Shielding to reduce sidelobe response

Cryogenic Receiver enclosure

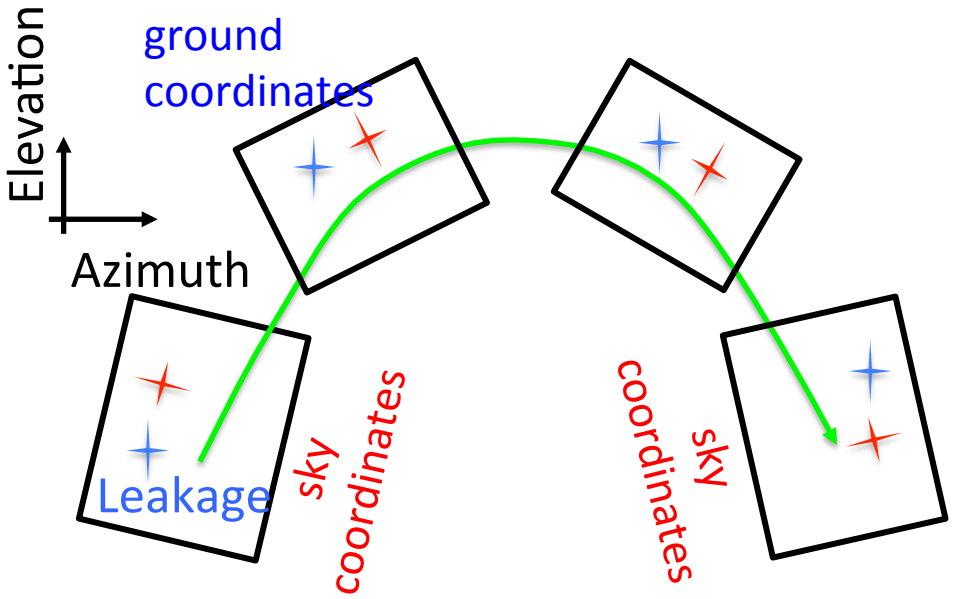
POLARBEAR Cryogenic Receiver



1274 superconducting TES bolometers (2 per pixel)

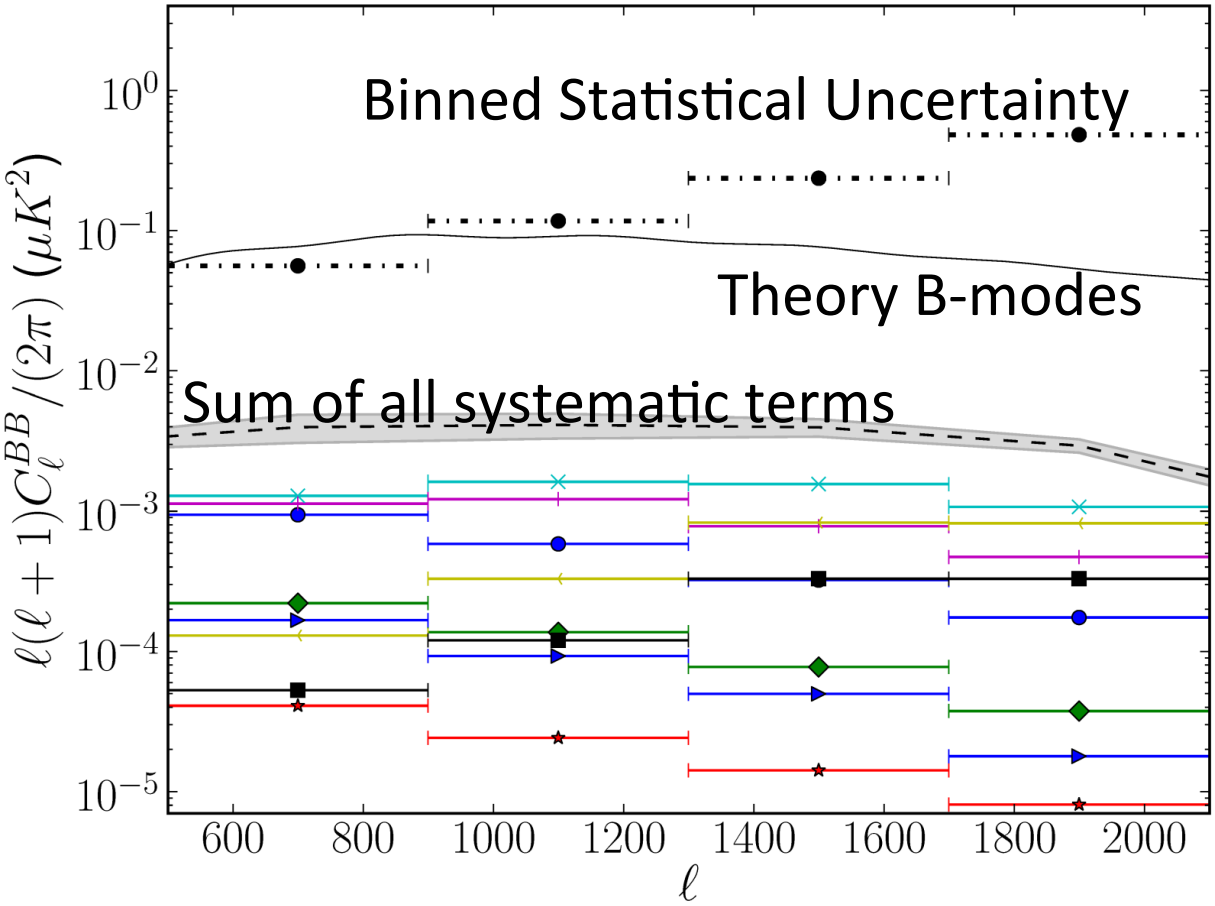
POLARBEAR: Control of systematic instrumental effects

- Instantaneous measurement of polarization with each pixel
- Modulation of CMB Polarization:
  - Half-wave plate
  - Apparent sky rotation
- Low sidelobe response
  - Co-moving baffling
  - Scan strategy allows ground removal



Instrumental Bias Estimation

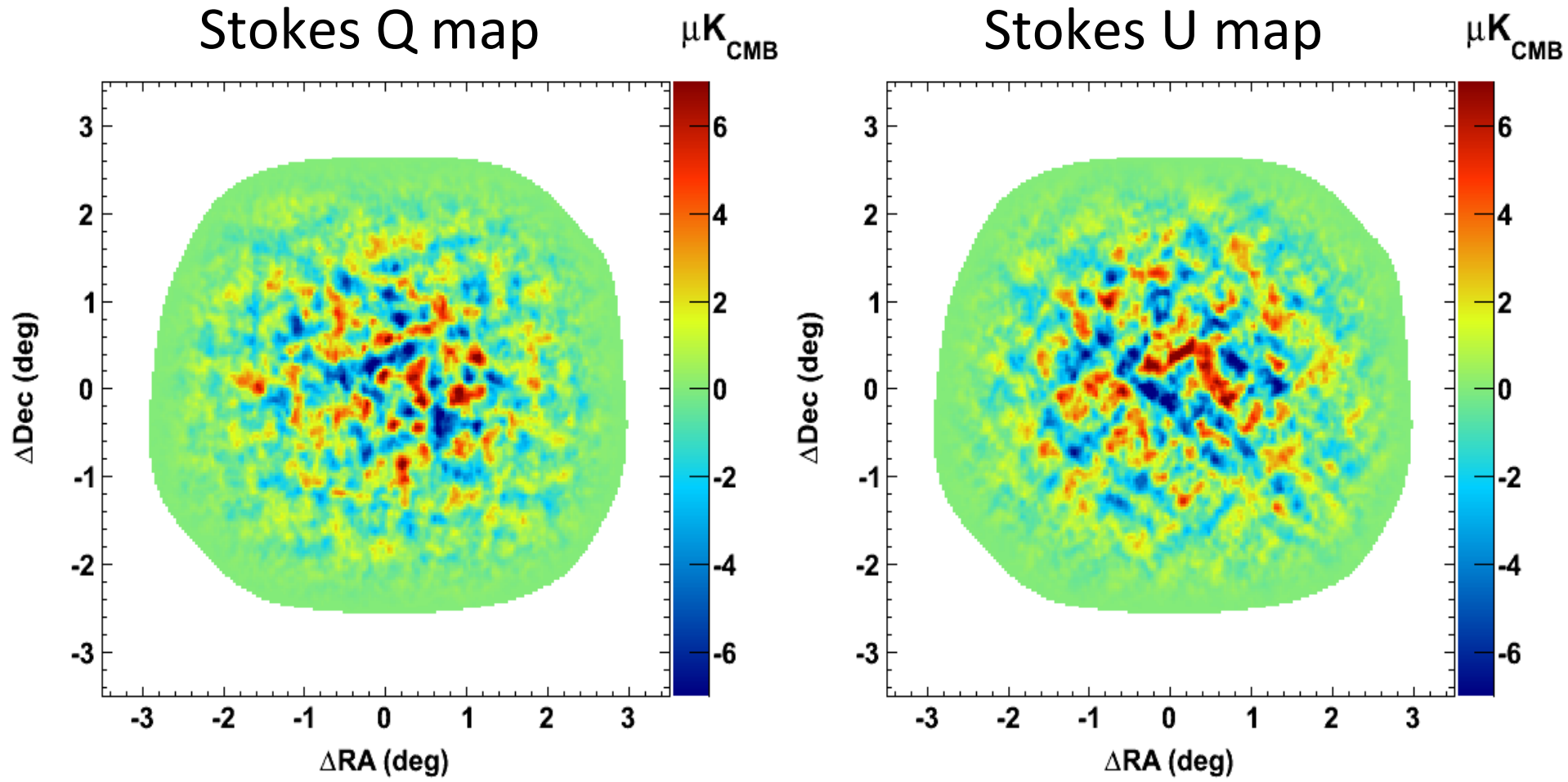
End-to-end simulations using measured instrument characteristics and cross-checks



Boresight & diff pointing
Differential beamsize
Polarization angle
Differential ellipticity
HWP-dependent gain
HWP-independent gain
Electrical crosstalk
Gain drift

Confirmed all known systematics are much smaller than statistical uncertainty before “unblinding” the spectrum

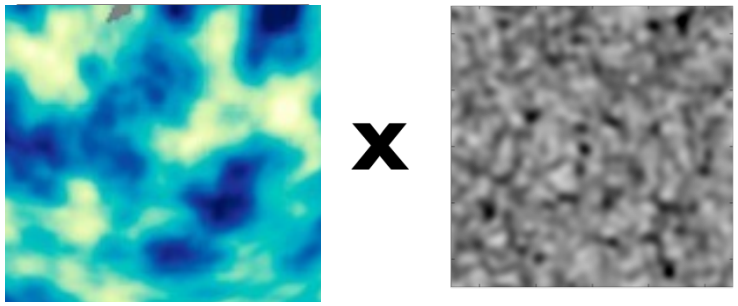
POLARBEAR First Season Observations



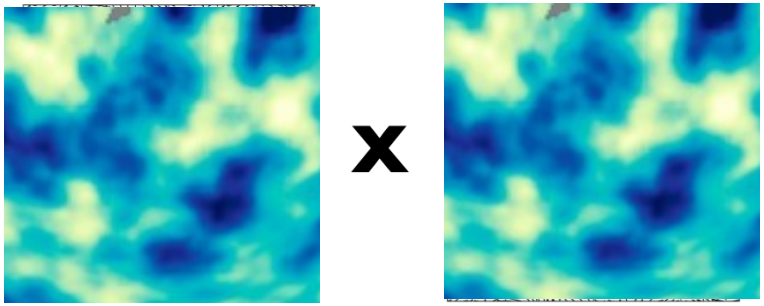
- Three fields, 24.5 deg^2 total sky area
- Map depth: 5.5, 8.5, 7.6 μK-arcmin
- Array sensitivity: 23 μK $s^{-1/2}$
- 13 calendar months of observations (May 2012 - June 2013)

First-Season POLARBEAR Results: Three B-mode Analyses

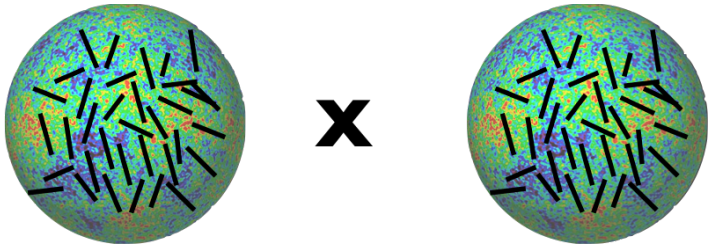
Galaxy cross-correlation:
PRL 112, 131302 (2014)



Deflection power spectrum:
PRL 113, 021301 (2014)

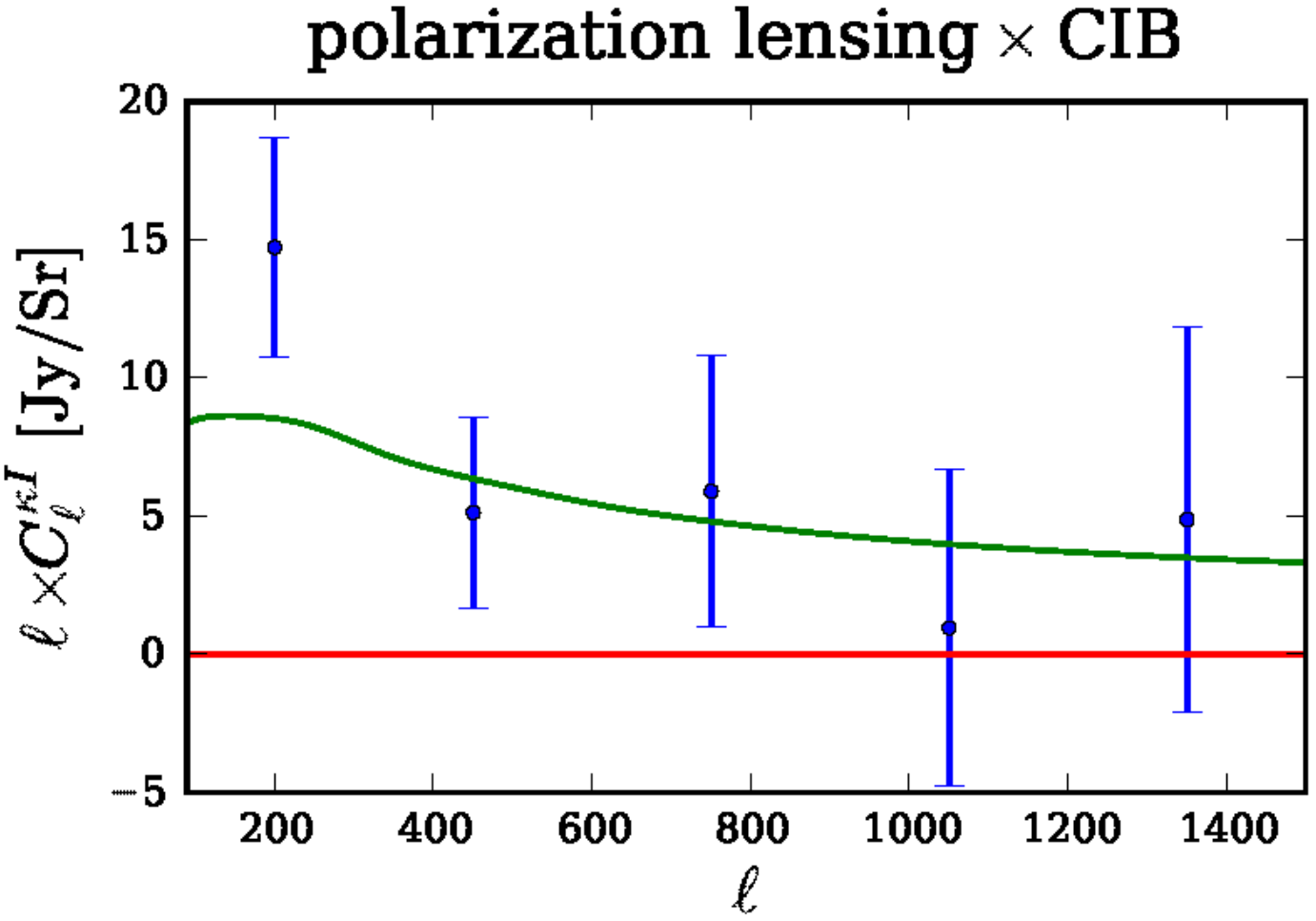


Angular power spectrum: C_ℓ^{BB}
ApJ 794, 171 (2014)



All Spectra available on NASA LAMBDA site
All analysis use 13 calendar months of observations (May 2012 - June 2013)

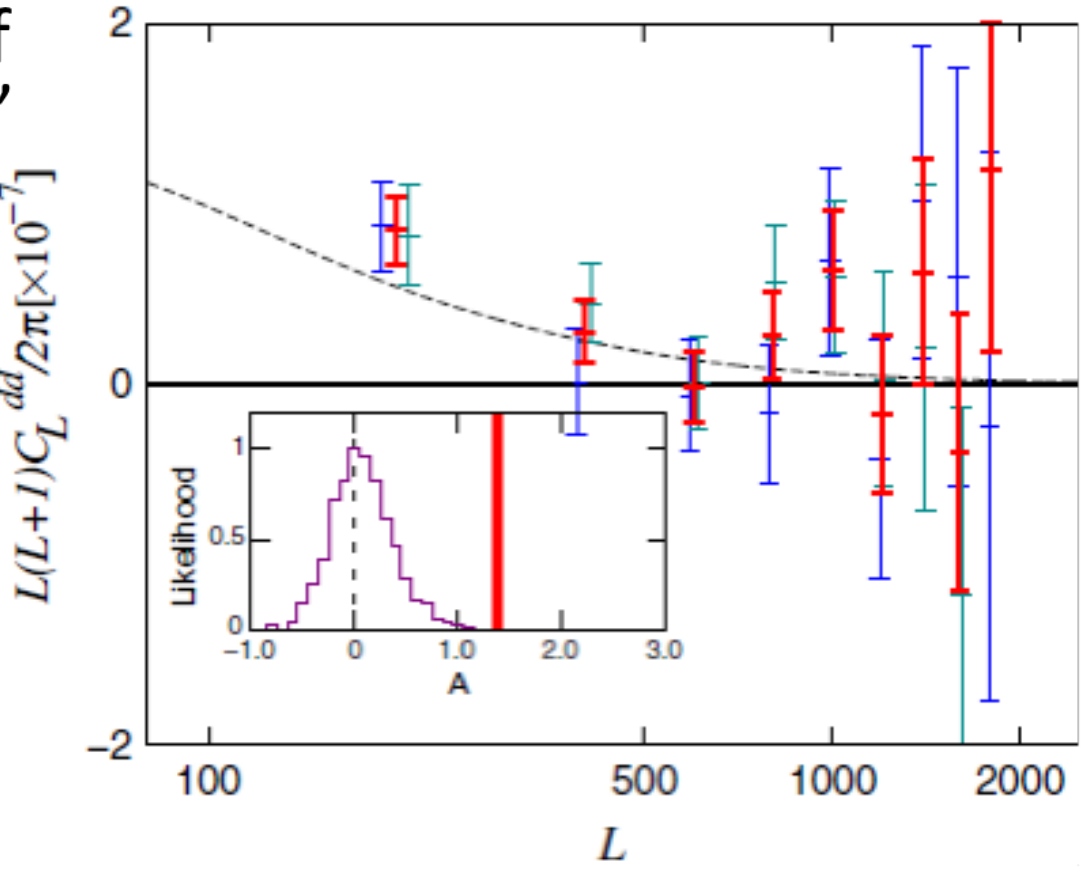
B-modes: Galaxy cross correlation



- 4.0σ evidence for gravitational lensing of CMB polarization
- Consistent with SPTpol measurement

B-modes: deflection power spectrum

- 4.2 sigma rejection of "no lensing *B*-modes"
- First reported CMB-polarization-only C_L^{dd} spectrum
- Polarization will be the most sensitive measure of C_L^{dd}
  - Groundwork for neutrino masses, dark energy



Green: $< EBEB >$

Blue: $< EEEB >$

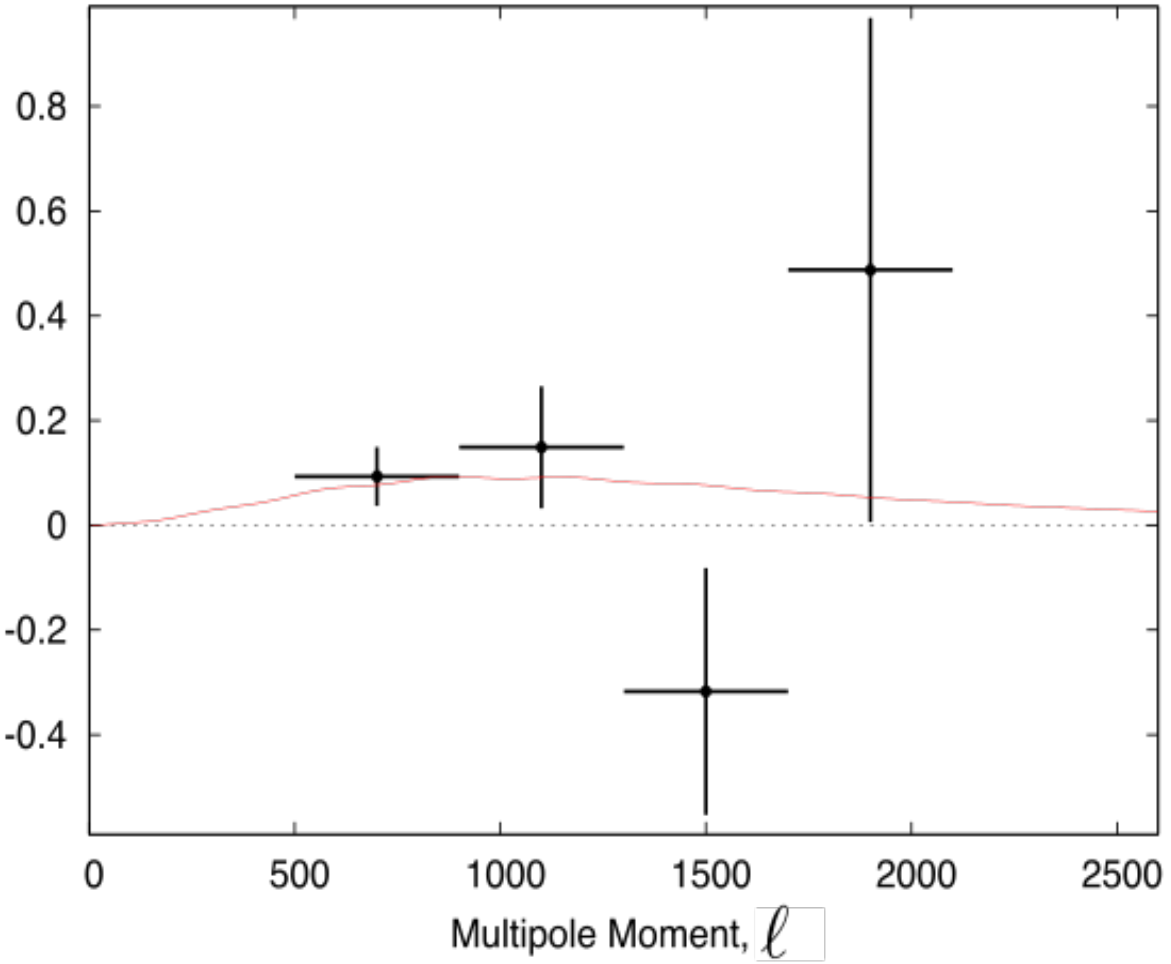
Red: Combined

B-modes: Power Spectrum C_ℓ^{BB}

97.2% rejection of "no lensing *B*-modes"

- including possible systematic instrumental biases
- Including estimate of foreground bias

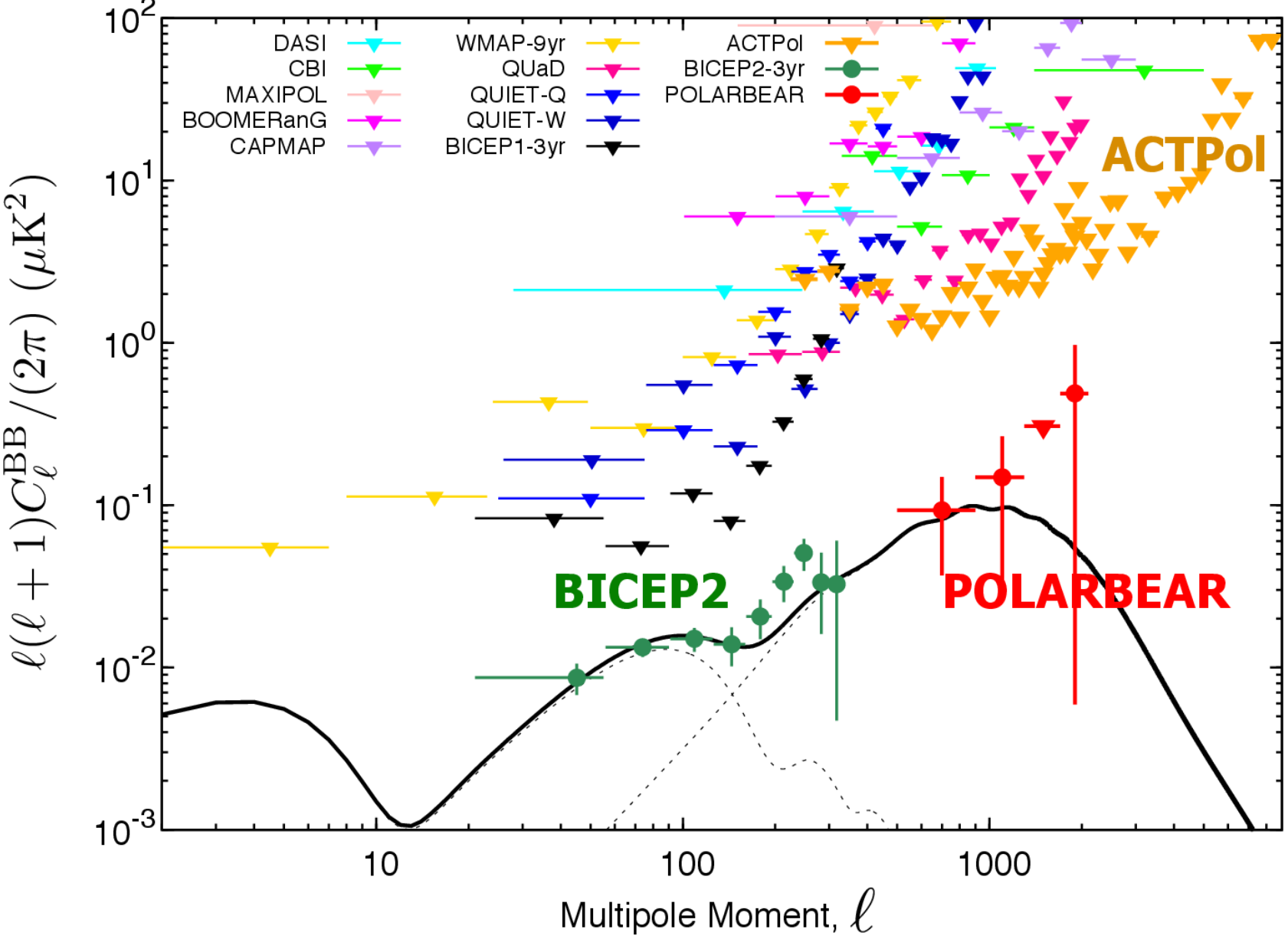
Combining three published results: 4.7σ rejection of "no lensing B-modes"



Amplitude of lensing compared to ΛCDM:

$1.12 \pm 0.61\ (stat)\ ^{+0.04}_{-0.12}\ (sys) \pm 0.07\ (mult)$

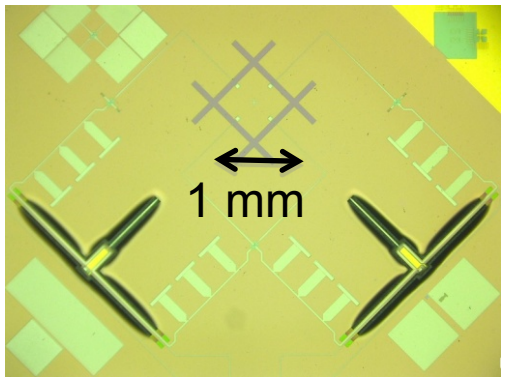
B-modes: Power Spectrum C_ℓ^{BB}

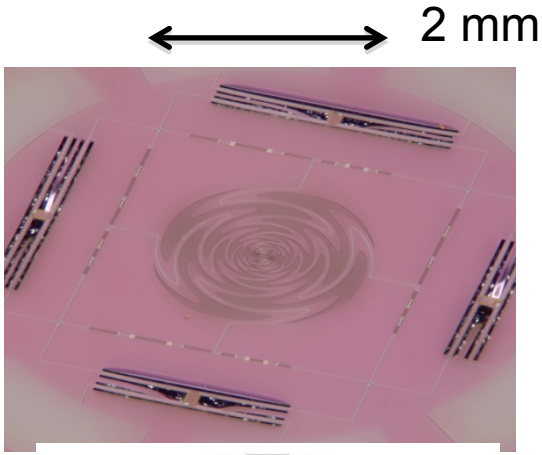


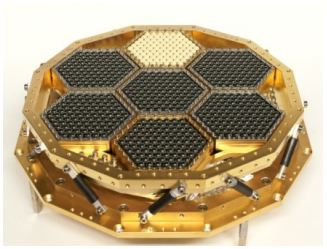
POLARBEAR -> Simons Array

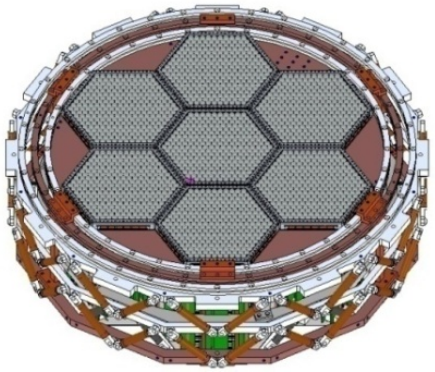
- Simons Array
  - Sensitivity: 22,768 total detectors
  - Resolution: 4’ sys. error advantage, measure lensing
  - Multi-chroic pixels with 90/150 and 150/220 GHz frequency coverage
  - Wide sky survey (f_{sky} = 65%)
  - Scalability: Future expansion possible (more telescopes and frequencies)

POLARBEAR-2: Sinuous Focal Plane







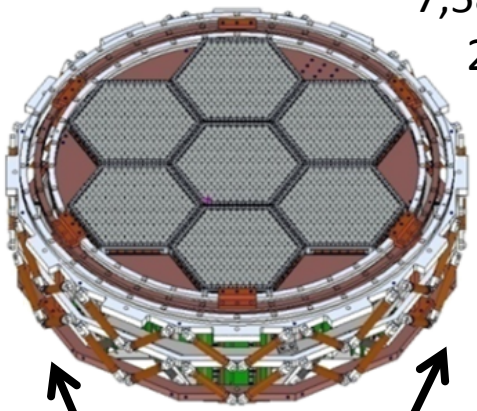


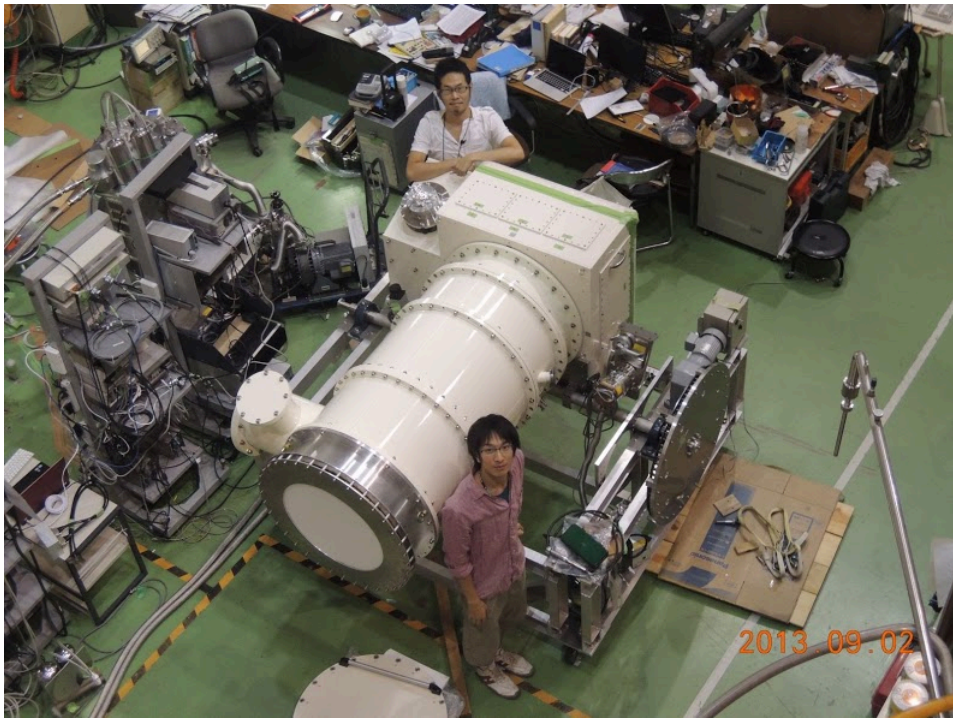
- POLARBEAR-1
- 1,274 Bolometers
- 150 GHz
- 22 cm diameter
- 4” wafers

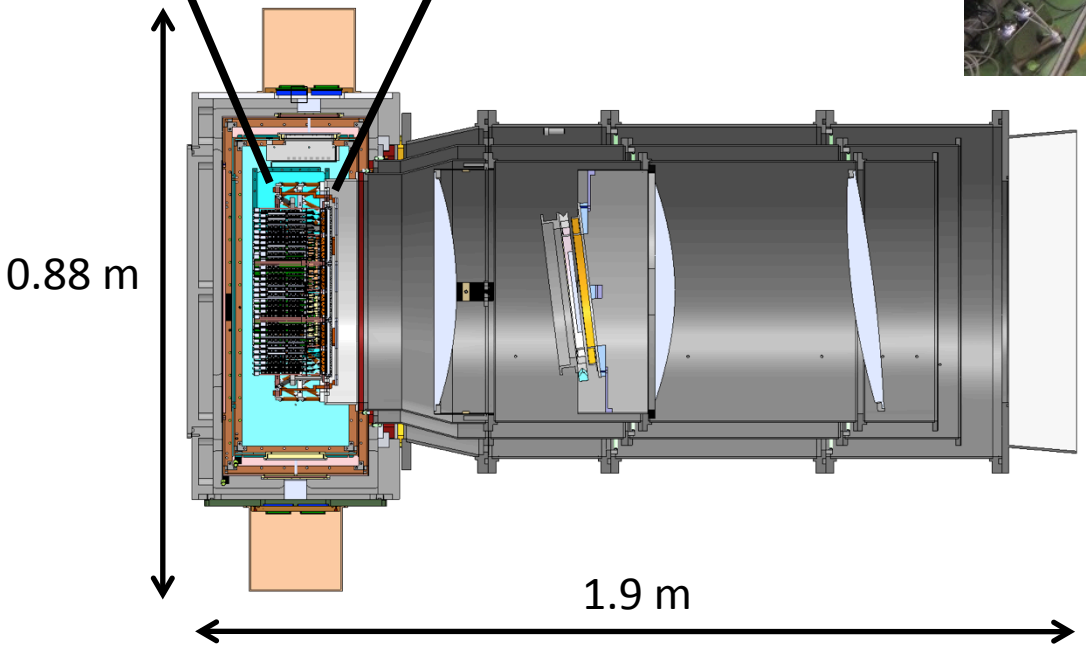
- POLARBEAR-2
- 7,588 Bolometers
- 95/150 GHz pixels
- 36.5 cm diameter
- 6” wafers

POLARBEAR-2 Receiver

365 mm diameter focal plane
7,588 bolometers
2-band Pixel



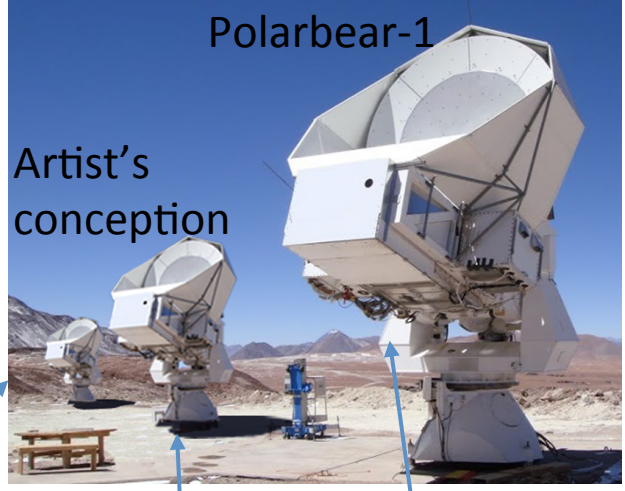




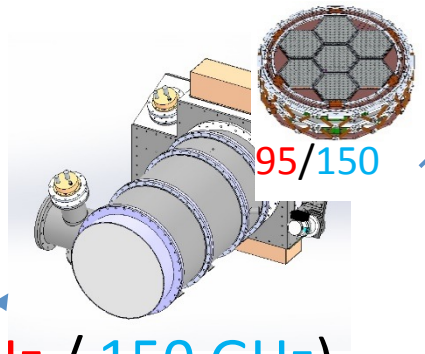
Lab tests underway of:
- Assembled cryogenic receiver
- Prototype detector sub-arrays
- 40x frequency multiplexed readout

The Simons Array

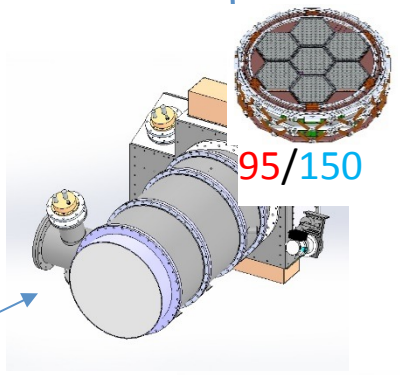
Leverage POLARBEAR experience to rapidly increase sensitivity



2014-2015: Construct two more telescopes

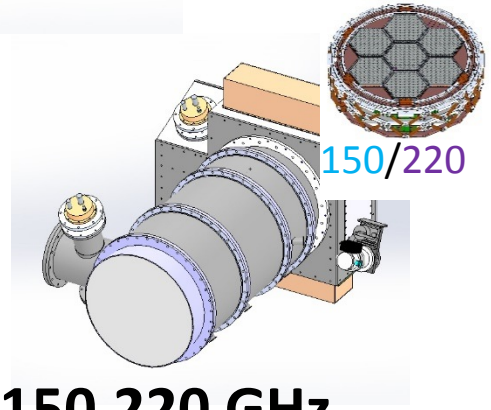


2015: POLARBEAR-2 (95 GHz / 150 GHz) deploys onto first new telescope



2016: A copy of POLARBEAR-2 deploys onto second new telescope

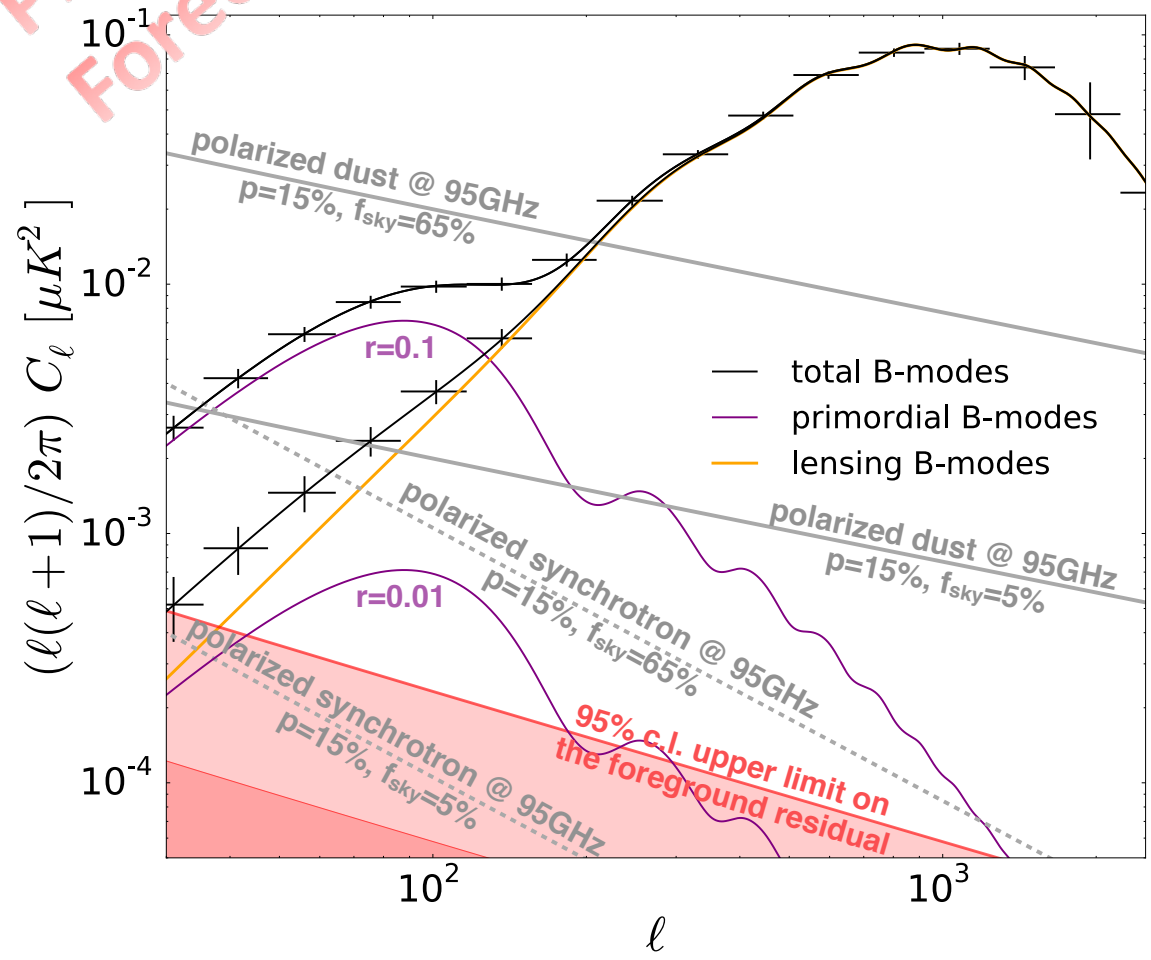
2016: A 150 GHz / 220 GHz receiver replaces POLARBEAR-1 on the original telescope



3 receivers (22,764 bolometers) observing at 95,150,220 GHz

All hardware funded by the Simons Foundation, MEXT, and NSF

Simons Array Sensitivity



Foreground rejection with 95/150/220 GHz, Planck, & C-BASS

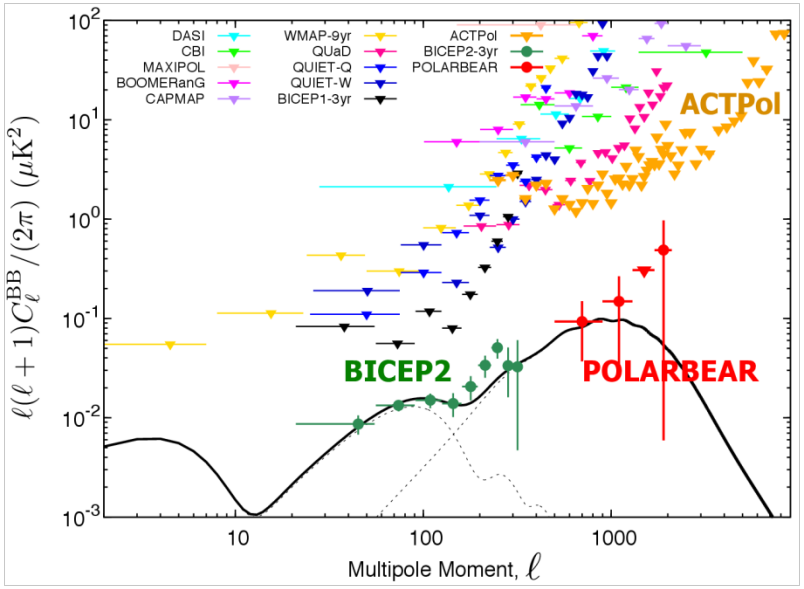
- $\sigma(r=0.1) = 6\times10^{-3}$
- $\sigma(n_s) = 6\times10^{-3}$

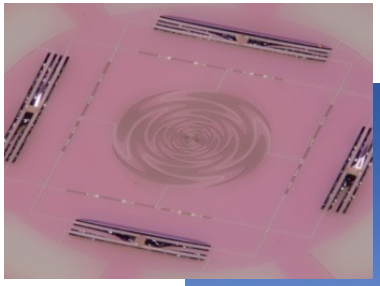
Neutrino Mass:

- $\sigma(\Sigma m_\nu) = 40$ meV (w/DESI BAO)

Residual computation method: Errard et al. 2011, Phys. Rev. D 84, 063005

In Summary…





- POLARBEAR-1: Three analyses showing B-modes (CMB alone: 4.7σ rejection of no lensing B-modes)
  - -CIB cross-correlation
  - -Deflection power spectrum
  - -C_l^{BB}

- Future: multi-chroic arrays in the Simons Array
  - - Increased sensitivity
  - -Foreground mitigation